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# STRUCTURAL TAILORING USING THE SSME/STAEBL CODE*

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Space Shuttle Main Engine (SSME) blades are subject to severe thermal, pressure, and forced vibration environments. An SSME blade design must meet tight clearance, fatigue life, and stress limit constraints. Because of the large number of potentially conflicting constraints, a "manual" design procedure may require many time-consuming iterations. Structural optimization provides an automated alternative. Any number of analyses, design variables, and constraints can be incorporated in a structural optimization computer code. This idea has been applied to develop the code SSME/STAEBL, which is a stand-alone code suitable for automated design of SSME turbopump blades.

SSME/STAEBL was developed by systematically modifying and enhancing the STAEBL (Structural Tailoring of Engine Blades) code developed by Pratt and Whitney under contract to NASA Lewis Research Center. STAEBL was designed for application to gas turbine blade design. Typical design variables include blade thickness distribution and root chord. Typical constraints include resonance margins, root stress, and root to chord ratios. In this program, the blade is loaded by centrifugal forces only.

Additions and modifications of STAEBL included in SSME/STAEBL include (1) thermal stress analysis, (2) gas dynamic (pressure) loads, (3) temperature dependent material and thermal properties, (4) forced vibrations, (5) tip displacement constraints, (6) single crystal material analysis, (7) blade cross section stacking offsets, (8) direct time integration algorithm for transient dynamic response. Capabilities are also included which permit data transfer from finite element models and stand-alone analysis.

Several design optimization studies have been completed using an SSME blade design to test these various capabilities. Optimization studies have been completed to test the influence of thermal and pressure loads and temperature dependent properties on optimal blade design. Comparison between designs optimized under centrifugal loads only and under centrifugal, thermal, and pressure loads with temperature dependent blade properties shows that the additional loads require additional weight to meet all design constraints. The difference between the designs can be attributed to material property temperature dependence, which in this case forces a much tighter root stress constraint.

Design optimization studies for a blade made of a typical single crystal material showed relatively little effect of crystal axis orientation. This

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study was dominated by a root stress constraint which was violated by the initial design. It was found that root stress is influenced much less by crystal orientation than by the geometric design variables. The result is that the optimized design is found by adjusting the blade geometry significantly, but the crystal axis orientation insignificantly. Of course, in blade designs dominated by natural frequency constraints in particular, a different conclusion could obtain.

Optimization studies were undertaken to assess the influence of blade cross-section offsets on optimal design. These offsets are defined as the differences between the blade cross section centers of gravity and a straight line perpendicular to the engine axis. Blade designers use these variables to balance centrifugal and pressure loads. In a typical optimization study, the initial design violated the root stress constraint. Root stress is extremely sensitive to offset variables, and the optimized design recommended a significant change in stacking.

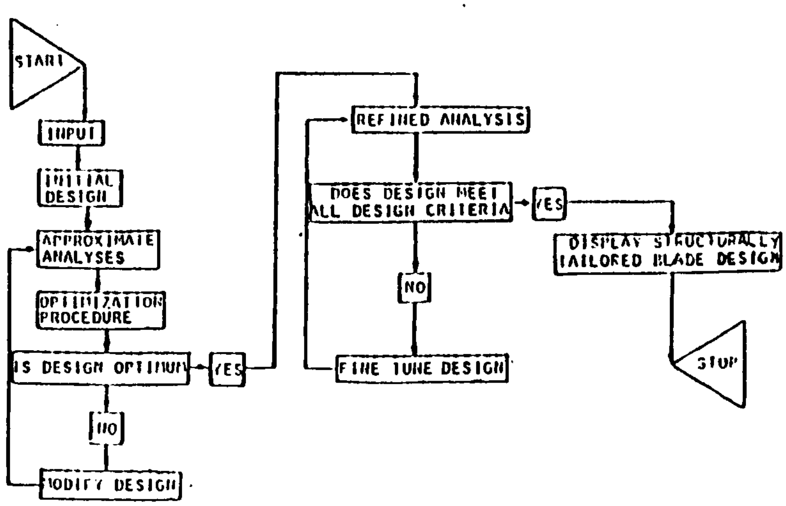
It can be concluded that structural optimization provides a practical and flexible approach to SSME blade design. The general structure of optimization algorithms allows many design variables, constraints, loads, and analysis options to be incorporated in the optimization procedure. In the design optimization studies reported here, which were dominated mainly by root stress constraints, it was found that temperature dependent properties can require additional weight in the optimized design, mainly by reducing the yield stress. Crystal axis orientation was relatively unimportant design variable in these studies. Blade cross-section stacking offsets were shown to have very significant effect on root stress-dominated designs. This conclusion agrees with the general experience of blade designers.

OBJECTIVE

Apply structural optimization methods to

SSME blade design.

STRUCTURAL TAILORING OF ENGINE BLADES (STAEBL)




STAEBL FLOW CHART

## OPTIMIZATION STUDY - SSME TURBOPUMP BLADE

### COMPARISON BETWEEN INITIAL AND OPTIMIZED DESIGN

| | INITIAL DESIGN | | | OPTIMIZED DESIGN UNDER CENTRIFUGAL LOADS ONLY | |
|---|---|---|---|---|---|
| %SPAN | THK (IN) | CHD (IN) | % SPAN | THK (IN) | CHD (IN) |
| 0. | .233 | 1.041 | 0. | .224 | .890 |
| 50. | .138 | .804 | 50. | .082 | .681 |
| 100. | .092 | .761 | 100. | .065 | .650 |
| NATURAL FREQUENCIES (CPS) | 3562. | | | 3454. | |
| | 4383. | | | 4868. | |
| | 7916. | | | 7969. | |
| ROOT STRESS (KSI) | | 83. | | 108. | |
| TIP DISPLACEMENTS | | | | | |
| UNTWIST (DEG) | | 2.28 | | 2.80 | |
| UNCAMBER (DEG) | | 1.22 | | 0.70 | |
| TIP EXT (IN) | | .0211 | | 0.0027 | |
| BLADE WEIGHT (LB) | | .056 | | .043 | |
| NUMBER OF BLADES | | 62 | | 73 | |
| STAGE WEIGHT (LB) | | 3.50 | | 3.14 | |

## OPTIMIZATION STUDY - SSME TURBOPUMP BLADE

### EFFECT OF THERMAL, PRESSURE LOADS AND FORCED VIBRATION ON OPTIMAL DESIGN

| | CENTRIFUGAL LOADS ONLY, TEMPERATURE INDEPENDENT PROPERTIES | | | REPRESENTATIVE THERMAL, PRESSURE LOADS TEMPERATURE DEPENDENT PROPERTIES | |
|---|---|---|---|---|---|
| % SPAN | THK (IN) | CHD (IN) | % SPAN | THK (IN) | CHD (IN) |
| 0. | .224 | .890 | 0. | .228 | .890 |
| 50. | .082 | .681 | 50. | .082 | .681 |
| 100. | .065 | .650 | 100. | .077 | .650 |
| NATURAL FREQUENCIES (CPS) | 3454. | | | 3174. | |
| | 4868. | | | 4438. | |
| | 7969. | | | 8835. | |
| ROOT STRESS (KSI) | | 108. | | 65. | |
| TIP DISPLACEMENTS | | | | | |
| UNTWIST (DEG) | | 2.8 | | 2.9 | |
| UNCAMBER (DEG) | | 0.7 | | 1.5 | |
| TIP EXT (IN) | | 0.0027 | | 0.0209 | |
| FORCED RESPONSE MARGINS | | .000 | | .592 | |
| | | .000 | | .557 | |
| | | .000 | | .010 | |
| BLADE WEIGHT (LB) | | .043 | | .044 | |
| NUMBER OF BLADES | | 73 | | 73 | |
| STAGE WEIGHT (LB) | | 3.14 | | 3.18 | |

## SINGLE CRYSTAL ANALYSIS

### EFFECT OF CRYSTAL ORIENTATION ON OPTIMAL DESIGN

| | CRYSTAL ALIGNED WITH ROOT CHORD | | CRYSTAL ALIGNED 45° TO ROOT CHORD | |
|---|---|---|---|---|
| % SPAN | THK. (IN) | CHD. (IN) | THK. (IN) | CHD. (IN) |
| 0 | .23 | .89 | .23 | .89 |
| 50 | .11 | .69 | .08 | .69 |
| 100 | .06 | .65 | .06 | .65 |
| FREQUENCIES (CPS) | 5110. | | 5079. | |
| | 6851. | | 6847. | |
| | 13540. | | 13870. | |
| ROOT STRESS (KSI) | 63. | | 65. | |
| STAGE WEIGHT (LB) | 3.26 | | 3.15 | |
| CRYSTAL ORIENTATION EULER ANGLES | | | | |
| $\alpha$ | .89 E-3 | | 45.00 | |
| $\beta$ | .57 E-2 | | -.20 E-1 | |
| $\gamma$ | -.51 E-3 | | .48 E-2 | |

## SINGLE CRYSTAL ANALYSIS

### GRADIENT OF ROOT STRESS CONSTRAINT AT FIRST ITERATION

| VARIABLE | GRADIENT |
|---|---|
| THICKNESS 1 | -.24 |
| THICKNESS 2 | -.16 |
| THICKNESS 3 | .01 |
| THICKNESS 4 | .04 |
| THICKNESS 5 | .01 |
| ROOT CHORD | 1.55 |
| EULER ANGLES | |
| $\alpha$ | .02 |
| $\beta$ | -.01 |
| $\gamma$ | .00 |

Optimization Study including blade stacking design variables

| Initial Design | | | | Final Design | | |
|---|---|---|---|---|---|---|
| % span | thk | chd | | % span | thk | chd |
| 0. | .233 | 1.041 | | 0. | .226 | .890 |
| 50. | .138 | .804 | | 50. | .134 | .688 |
| 100. | .092 | .761 | | 100. | .091 | .650 |

blade stacking

| Initial Design | | Final Design | |
|---|---|---|---|
| A = 0. | B = 0. | A = -.0012 | B = .0078 |
| C = 0. | D = 0. | C = .0013 | D = .0095 |

Root Stress

| Initial Design | Final Design |
|---|---|
| 82. ksi | 74 ksi. |

z axis along span, blade length = L

$\Delta x$ = x displacement from center of gravity

$\Delta y$ = y displacement from center of gravity

$$\Delta x = A\,(z/L) + B\,(z/L)^2$$

$$\Delta y = C\,(z/L) + D\,(z/L)^2$$

Comparison between effects of thickness, root chord, and blade stacking on root stress.

Optimization run with root stress constraint violated by initial design

| | Design Variable | Gradient of Root Stress |
|---|---|---|
| | thk 1 (root) | -.21 |
| | thk 2 | -.25 |
| | thk 3 | .00 |
| | thk 4 | .02 |
| | thk 5 (tip) | .00 |
| | root chord | 1.28 |
| blade stacking | A | 9.20 |
| | B | 8.77 |
| | C | 2.39 |
| | D | 2.82 |